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ULTRA-HIGH BYPASS RESEARCH

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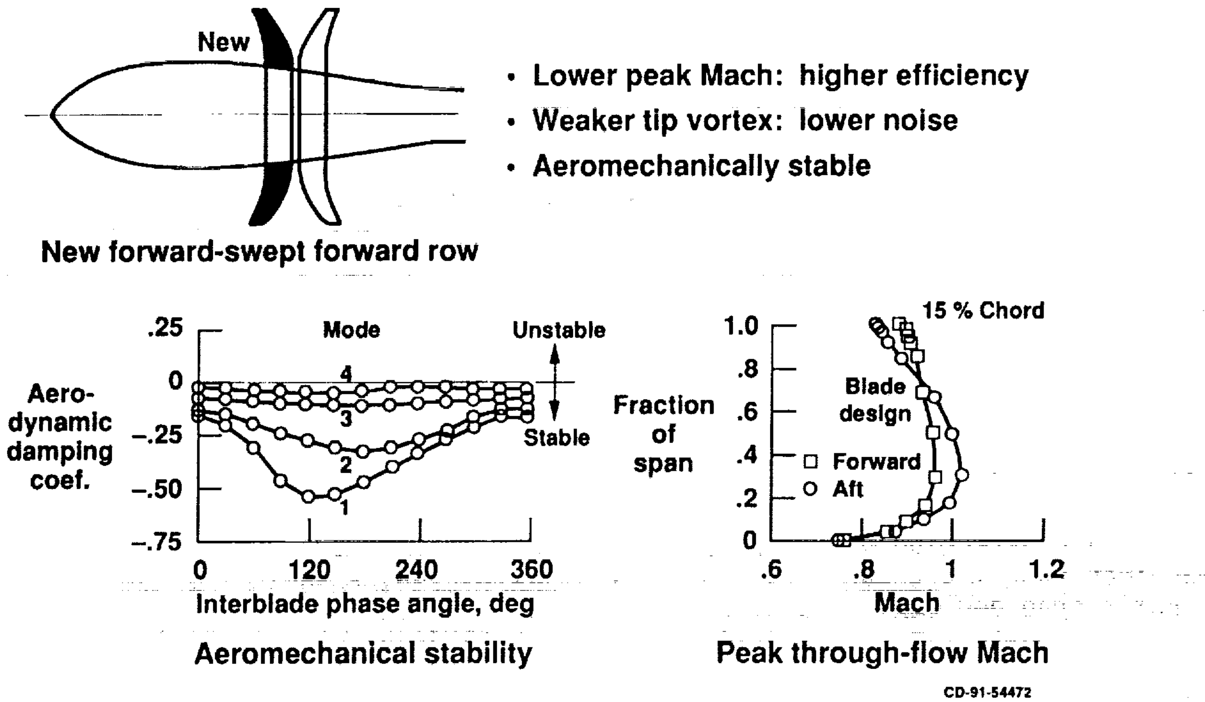
This paper presents an overview of the ultra-high bypass research at the NASA Lewis Research Center. Over the past decade, the program was focused on unducted rotors and precipitated several development efforts in industry. In this area, forward-swept unducted rotors are the concluding effort. Forward sweep can reduce the tip vortex strength and has a potential for reducing the noise of counter-rotating unducted rotors. The aerodynamic performance can also be improved slightly over an aft-swept blade.

The future direction of the program is toward ultra-high bypass ratio ducted machines, and short cowls as a particular item. Short cowls can have less aerodynamic drag and less weight, but may allow more noise to be radiated. In general, the aerodynamic research effort will be to provide higher efficiencies, sufficient flow conditioning, and attached flow at high angles of attack. Acoustically, the research is directed towards developing an understanding of fan acoustics in short ducts. The reduced duct length means that there might be insufficient duct length for acoustic cutoff. With less length and less cowl thickness, the space for acoustic treatment is limited, requiring integrated aeroacoustic designs.

Advanced Unducted Aerodynamics

Forward-Swept Counterrotation Concept



The current program in advanced unducted propfan concepts is concluding with a study of the effect of forward sweep on noise and aerodynamic performance. A counterrotation configuration is used with new forward-swept front blades and existing aft-swept rear blades. The new blades are designed to have the same loading as the original aft-swept front blades.

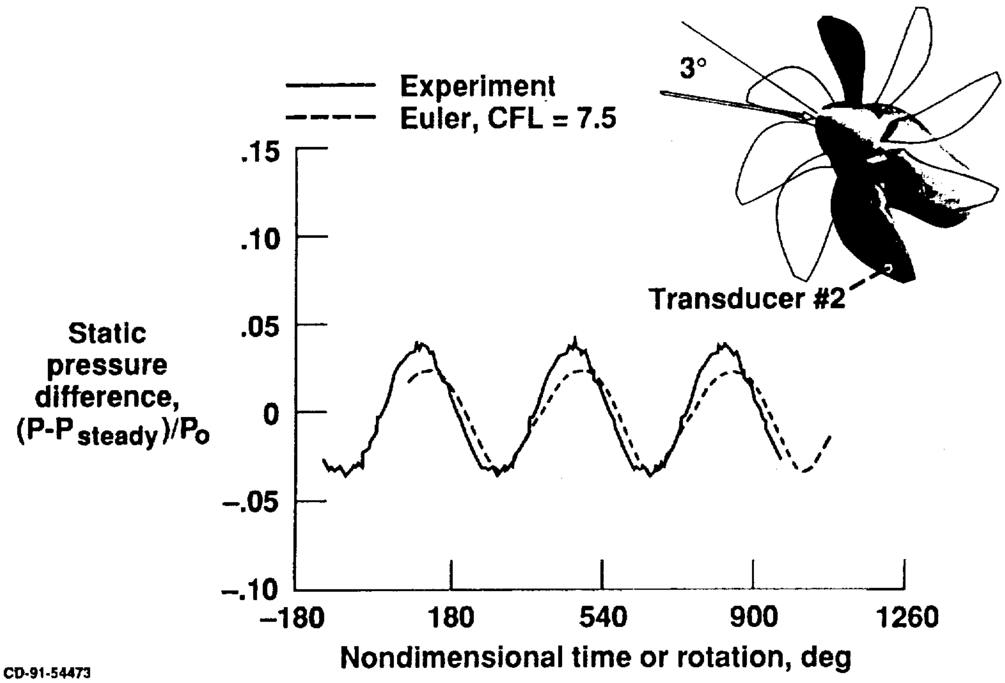
Aerodynamically, several effects from forward sweep are seen. Forward sweep places the blade tip in a region of slightly lower axial velocity which reduces the section Mach numbers and also evens out the radial distribution of peak through-flow Mach number, resulting in higher efficiency. The tip vortex development is strongly effected by sweep. An aft-swept blade, particularly with the leading edge vortex (LEV) present at high-lift/off-design conditions, has a very strong tip vortex. Significant amounts of low-energy fluid are collected off the blade and produce a large low speed core. In comparison, the forward-swept blade will have separate leading edge and tip vortices with the boundary layer fluid primarily in the LEV.

A strong noise source is the front-row tip vortex interacting with the aft-blade row. This acoustic source is dependent on the vortex strength and is stronger with increasing radius. Here, the forward-swept blade provides specific benefits: the tip vortex is much weaker, and the separate LEV, when present, will interact with the aft blades well inboard of the tip. The increased spacing between the blade rows at the tip should decrease noise, whereas the proximity of the blades near the hub increases the potential field interaction noise.

Aeromechanically, the forward-swept blade is stable throughout the operating range.

Unsteady Aerodynamics

SR7 2-Bladed Propfan Modane Test Case (M = 0.8, J = 3.06, AOA = 5°)
Unsteady surface pressure (fine grid)



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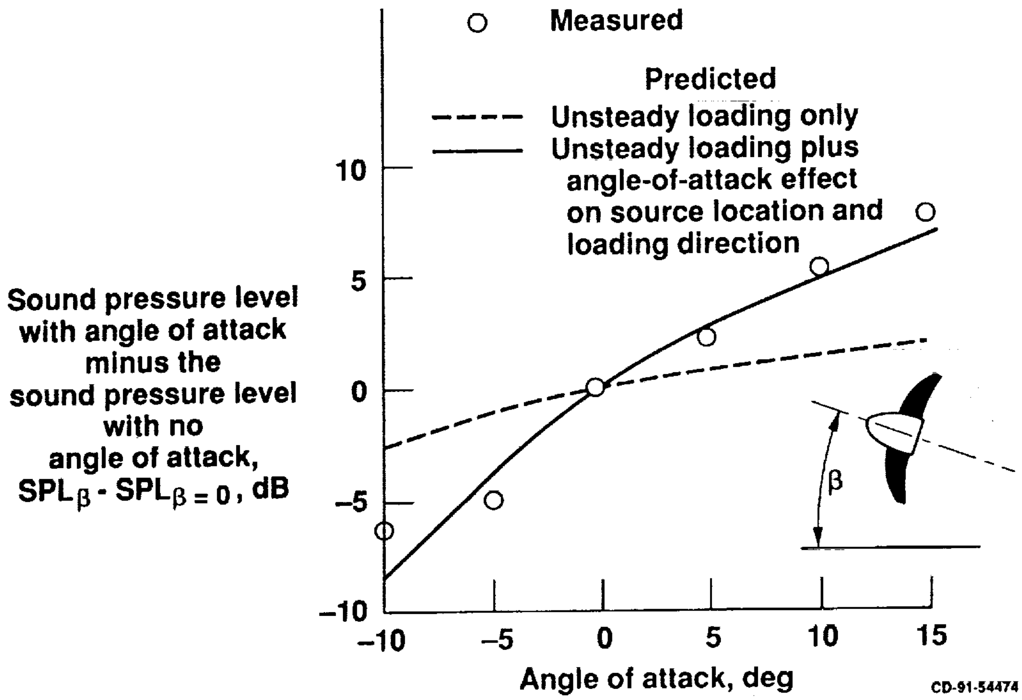
Unsteady blade surface pressures are needed to predict angle-of-attack performance and as input for acoustic calculations. Several computer codes now provide very good predictions of these pressures. For example, a full-scale, single-rotation SR-7 propfan was tested at Modane, France to provide unsteady blade surface pressures. For the test point shown, a highly loaded climb-out condition, model drive power constraints prevented reaching the correct blade loads with more than two of the eight blades. Euler calculations by Nallasamy (ref. 1), and by the Allison Gas Turbine Division of General Motors Corp. (shown) provide very good agreement with the experimental data.

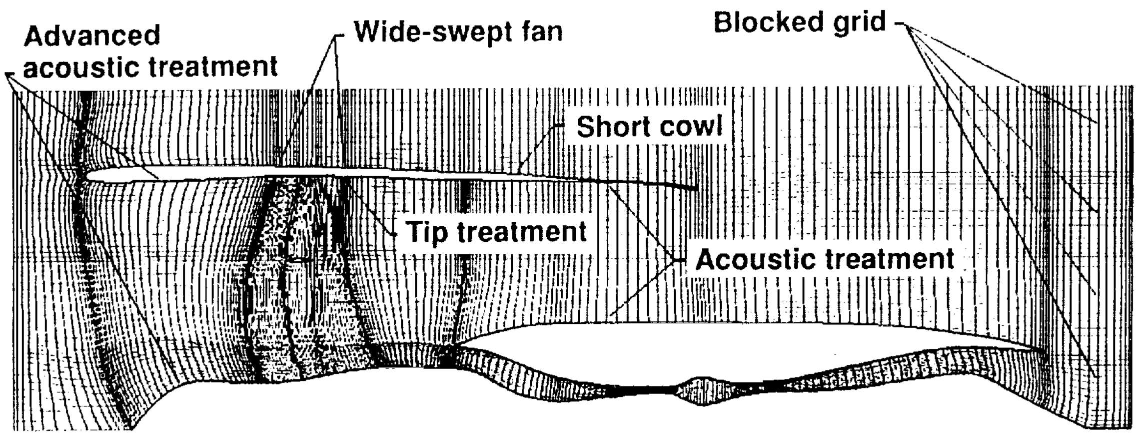
Angle-of-Attack Noise Prediction



When provided with good unsteady loading information, noise prediction techniques can now accurately predict the unsteady noise of a propfan at an angle of attack. Mani (ref. 2) developed an analysis that predicted the change in noise as a function of angle of attack due to both the steady and unsteady loading. The analysis includes the azimuthal variation of the radiation efficiency of the steady noise sources. This analysis, however, was limited to small angles of attack. Krejsa (ref. 3) extended the work to be valid at large angles of attack. When results from Krejsa's analysis are compared with the data of Woodward (ref. 4), the significant improvement in prediction accuracy is evident.

Ultra-High Bypass Directions

- Develop high-efficiency propulsors
- Lower noise than current technology
- Higher fan pressure ratios
- Lower fan tip speeds



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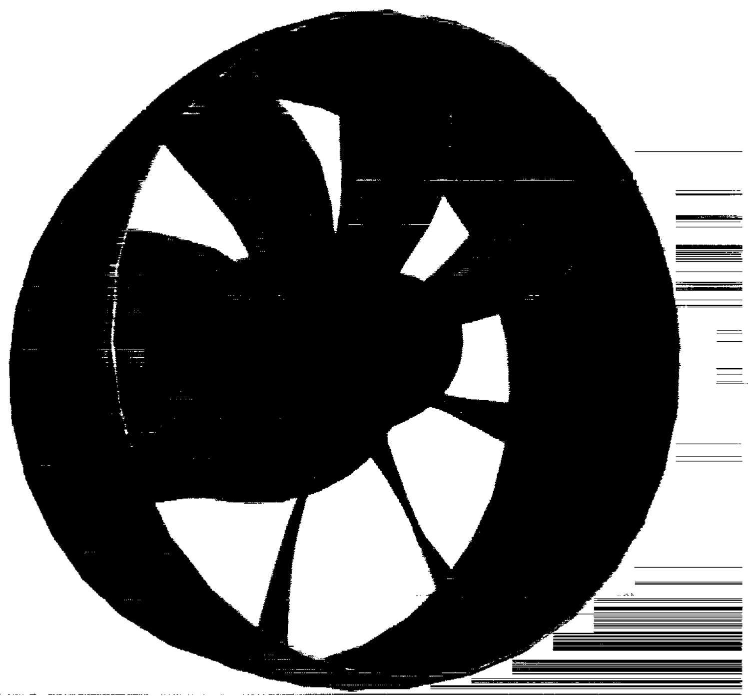
Advanced unducted propfans show significant performance gains over older unducted technology, but diameter constraints and the need for higher thrust levels have shifted NASA's research to ducted configurations again. The goal now is to obtain higher efficiencies and lower noise than current technology by using the lessons learned with unducted concepts. To address higher thrusts with constrained diameters, higher fan pressure ratios are a priority, but they incur an efficiency and noise penalty. Current aerodynamic research focuses on fans with a lower number of wide-chord swept blades, significantly shorter cowls, and tip treatments. Lower fan tip speeds are seen as the primary driver to reduce source noise. Acoustic research concepts include advanced acoustic treatments, nonaxisymmetric arrangements, and active controls.

To evaluate these new concepts, NASA is developing computational fluid dynamics (CFD) codes for ducted high-bypass fan sections under contract to the Allison Gas Turbine Division of General Motors Corp. (ref. 5). This group of Advanced Ducted Propfan Analysis Codes (ADPAC) handle steady and unsteady inflows with the Euler and Navier-Stokes equations in average-passage or time-accurate formulations. Currently under development is a code using a blocked grid that will solve for the internal (fan flow), external, and core flow about a realistic engine configuration - the NASA E^3 engine. A parallel effort is underway within NASA to incorporate acoustic models for noise generation and propagation so that one code will provide fluid mechanical and aeroacoustic evaluation of these concepts.

Ducted Propfan at Angle of Attack



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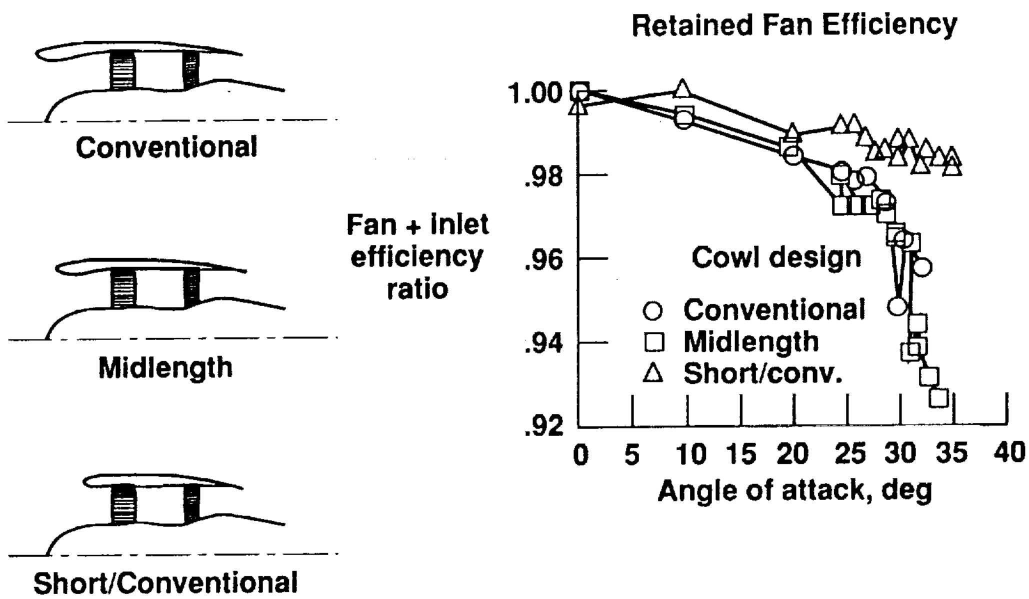
A demonstration geometry for the ADPAC codes was created by taking the NASA single-rotation SR7 blade geometry, clipping it at the 75-percent span, and placing it in a representative short cowl. There is a tip gap of about 2-percent span. The flow conditions are Mach 0.8, advance ratio of 3.12, and axis of rotation at 5° to the inflow.

The Euler calculation used a somewhat coarse mesh with 20 points per chord line. The flow solution required approximately three revolutions to reach a consistent time history and took 20 hr of Cray Y-MP time. The surface static pressure shows the asymmetric loading due to angle of attack.

Because of the long times required for fine-mesh calculations, the development of the codes will be directed towards parallel processing.

Advanced Ducted Propeller Test Results

Angle of Attack Effects by Cowl Length



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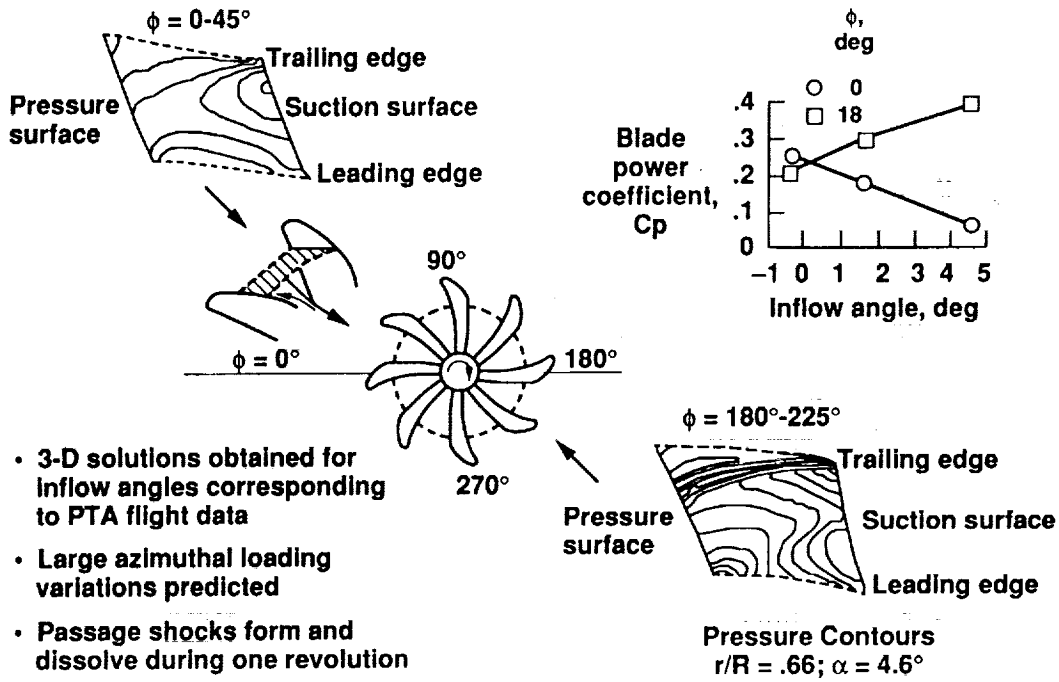
Under terms of a space act agreement, Pratt & Whitney Aircraft and NASA are testing an Advanced Ducted Propeller (ADP) concept model to evaluate ducted propfan performance with shorter, low-drag cowl designs. The results show that very short cowls have desirable aerodynamic features. Shown is the combined fan plus inlet efficiency ratioed to the value at zero angle of attack. Although the long cowl can do a better job of reducing distortion, it will also develop more of a boundary layer. Also, at the high angles of attack, the short cowl appears to have less separated flow coming into the fan. The preliminary data show that the combined short-length cowl/conventional spinner + fan performs well at high angle of attack: the short cowl and fan have the same efficiency reduction at 35° as the conventional and midlength cowls have at 20°. It is not clear whether this high angle-of-attack performance is due to the reduced cowl separation or to retained fan efficiency.

CFD Calculations

Unsteady Euler Analysis of the Flow Field of a Propfan at an Angle of Attack



- 3-D solutions obtained for inflow angles corresponding to PTA flight data
- Large azimuthal loading variations predicted
- Passage shocks form and dissolve during one revolution

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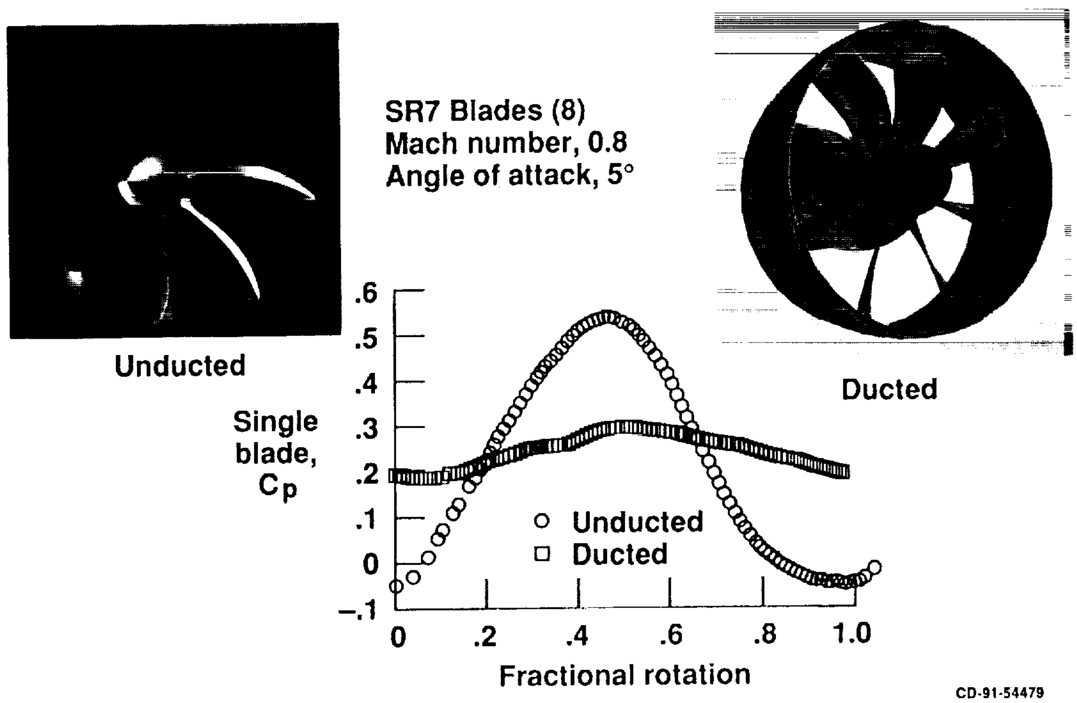
Angle-of-attack Euler code predictions provide insight into experimental results obtained in the Propfan Test Assessment (PTA) flight test program (ref. 6). The Euler predictions show large azimuthal loading variations, a strong driver in noise generation. The strongest driver is the unsteady nature of the passage shock. On the highly loaded downward portion of the revolution, a strong passage shock forms and is attached to the trailing edge on the suction surface of the blade. This is the portion of the blade rotation where the generated noise is directed downwards towards the "community." On the upward moving side, the passage shock dissolves, reducing the noise directed towards the cabin. The predictions show that at cruise Mach numbers relatively small inflow angles can produce very large blade-loading variations. If the flow were straightened, as by a short cowl, the unsteady loading and, thus, the noise would be significantly reduced at nominal angle-of-attack conditions.

These loadings have been used as input to an acoustic code to predict near field noise levels (ref. 7). Qualitatively, the effect of inflow angle is correctly predicted.

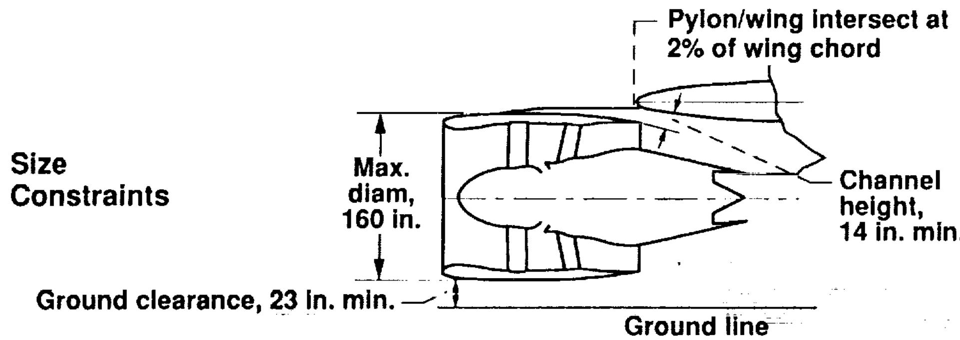
Unsteady Aerodynamics

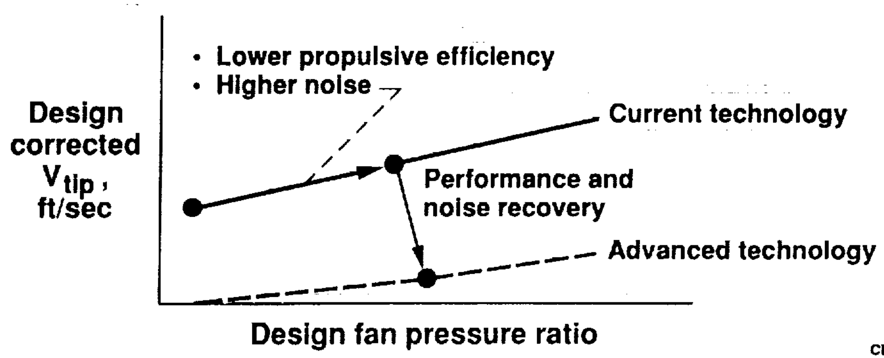
Duct Reduces Unsteady Loading



The flow-straightening effect of a short cowl is demonstrated by a side-by-side comparison of similar propfans. The unducted propfan is the SR7 with eight blades operating at Mach 0.8 and an angle of attack of 5°. This is a relatively high-loading condition. The ducted propfan is based on the SR7 blade, clipped at 75-percent span, and operating at the same conditions as the unducted SR7. The plot of normalized-blade power loading shows that the cyclic variation of loading is about five times larger for the unducted propfan.

New Cycles





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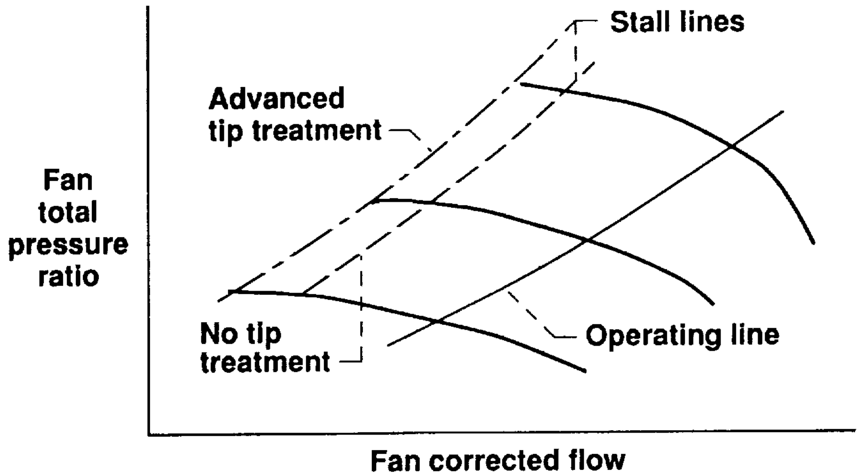
The need for larger thrust engines for twin-engine, long-range aircraft is constrained by engine diameter. Further, to reduce the fan noise level, one of the most effective techniques is the reduction in fan tip speed. Designers are therefore presented with the task of reducing fan tip speed while increasing fan pressure ratio. Shown is a result from a Pratt & Whitney cycle study to identify current directions and critical technology items. Note that the desired change in fan pressure ratio and fan tip speed is a significant change from current technology. To operate at these highly loaded conditions, fan surge and stall margins are even more important.

Casing Treatments

Fan Showing Improved Stall Margin



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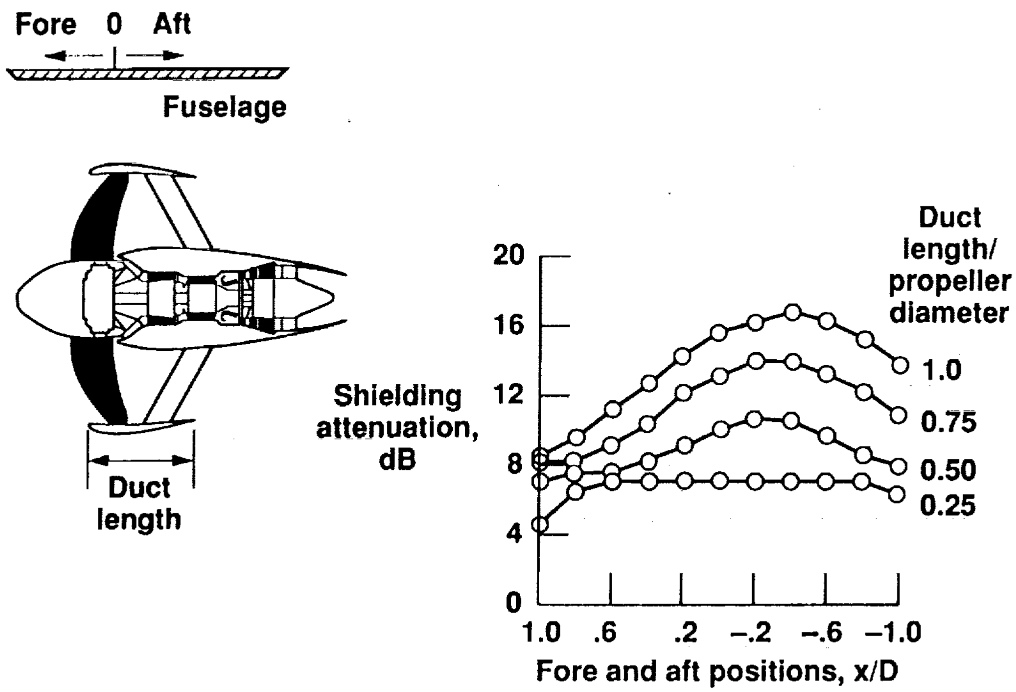
Higher fan pressure ratios and lower fan tip speeds increase the blade loading everywhere, especially at the tip. Advanced casing treatments can improve the surge margin and stall performance by delaying separation and stall at the tip. The Pratt & Whitney cycle study evaluated the performance of an advanced tip/casing treatment. This treatment provides not only a significant improvement in surge margin but has almost no aerodynamic efficiency penalty. Stall margin can be a problem with current technology since the stall margin is decreased as the fan loading is increased. By using tip treatments, though, current stall margins can be maintained at the higher loadings needed for future engines.

On design, tip treatments must have low losses and may reduce noise by reducing the strength of or promoting the dissipation of the tip vortex. Weaker vortices reduce the unsteady loading on stators/EGV's, which can reduce noise.

Predicted Short-Duct Noise Shielding



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The acoustic shielding provided by a cowl has a large effect on cabin noise. To evaluate short-duct acoustic shielding for a wing-mounted engine, a simple barrier-shielding model was used to estimate the noise on the fuselage (ref. 8). With the propeller located one-third of the duct length from the inlet, estimates for the maximum blade passing tone attenuation varied from 7 dB for a duct length of 0.25 D (propeller diameter, D) to 16.75 dB for a duct length of 1 D. Attenuations for the higher harmonics would be even larger because of their shorter wavelengths relative to the duct length. These estimates show that the fuselage noise-reduction potential of a ducted, as compared with an unducted, propeller is significant even for very short duct lengths.

Summary

- Unducted rotor research concluding
- Emphasis shifting to ducted configurations
- Initial short-duct aerodynamic results encouraging
- Developing aeroacoustic understanding of props and fans in short ducts
- CFD analysis tool development emphasizing integrated calculations for rotors in short cowls

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Forward sweep can reduce the tip vortex strength and, hence, has a potential for reducing the noise for counter-rotating unducted rotors. The aerodynamic performance can also be improved slightly over an aft-swept blade.

Short cowls have most of the aerodynamic advantages of conventional cowls with very few disadvantages. Experiments show that they do a good job of flow straightening and have delayed lip separation as compared with conventional length cowls. The reduced length also means less boundary layer buildup, less weight, and less drag.

NASA's acoustic research effort is currently directed towards developing an understanding of propeller/fan acoustics in short ducts. The reduced duct length means that there might be insufficient duct length for acoustic cutoff. With less length and less cowl thickness, the space for acoustic treatment is limited, requiring integrated aeroacoustic designs.

Continuing CFD analysis tool development will provide Euler and Navier-Stokes codes for advanced high-bypass ratio engine concepts. These tools, which do an integrated calculation of the rotor and cowl flow fields, will handle steady inflow as well as angle-of-attack calculations.

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